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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 10563, 105631D · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304230

FIBER OPTIC SENSING SUBSYSTEM FOR TEMPERATURE MONITORING IN SPACE IN-FLIGHT APPLICATIONS

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I. INTRODUCTION

Fiber Optic Sensor (FOS) technology presents long recognized advantages which enable to mitigate deficient performance of conventional technology in hazard-environments common in spacecraft monitoring applications, such as: multiplexing capability, immunity to EMI/RFI, remote monitoring, small size and weight, electrical insulation, intrinsically safe operation, high sensibility and long term reliability. A key advantage is also the potential reduction of Assembly Integration and Testing (AIT) time achieved by the multiplexing capability and associated reduced harness.

In the frame of the ESA’s ARTES5.2 and FLPP-Phase 3 programs, Airbus DS-Crisa and FiberSensing are developing a Fiber Bragg Grating (FBG) – based temperature monitoring system for application in space telecommunication platforms and launchers. The development encompasses both the interrogation unit and the FBG temperature sensors and associated fiber harness.

In parallel Airbus DS - Crisa is developing a modular RTU (RTU2015) to provide maximum flexibility and mission-customization capability for RTUs maintaining the ESA’s standards at I/O interface level [1]. In this context, the FBG interrogation unit is designed as a module to be compatible, in both physical dimensions and electrical interfaces aspects, with the Electrical Internal Interface Bus of the RTU2015, thus providing the capability for a hybrid electrical and optical monitoring system.

II. FBG INTERROGATOR

The FBG interrogator (Interrogation Unit, IU) is the opto-electronic unit that is in charge of illuminating the fiber and of identifying the reflected wavelengths and converting them into the physical parameters to be measured (e.g. temperature). The IU also provides the communication interface required to transmit the acquired parameters to the TM sub-system (TMSS).

A. Interrogation unit architecture

The interrogation unit uses a FiberSensing proprietary tunable laser to sweep a broad spectral range (100nm from 1500 to 1600nm), covering all the design wavelengths of the sensors multiplexed along the same fiber. The equipment has multiple redundant optical channels (up to 6), enabling the simultaneous addressing of up-to 120 sensors. Each channel includes an independent protection against single-point failure of the associated fiber. The functional diagram of the interrogation unit is depicted in Figure 1.

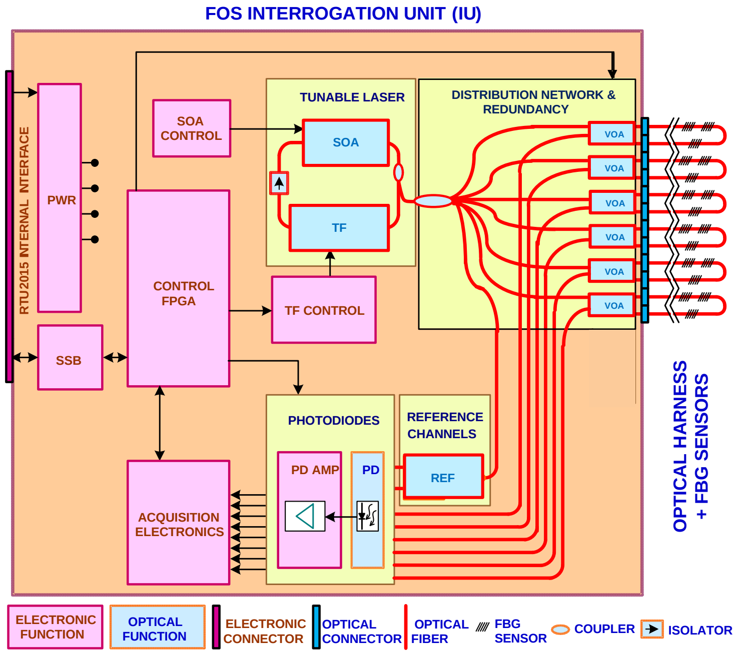


Fig. 1. Functional diagram of the IU

As already stated, the FBG interrogation unit is being designed as a module for Crisa's RTU2015, and thus target form factor and interfaces of the unit are compatible, in both physical dimensions and electrical interfaces aspects, with the Electrical Internal Interface Bus of the Modular RTU. The FOS module contains the electronic components in one section and the electro-optical/optical components in a different section, taking the space of two slots of the RTU. The mechanical layout of the module is shown in Figure 2.

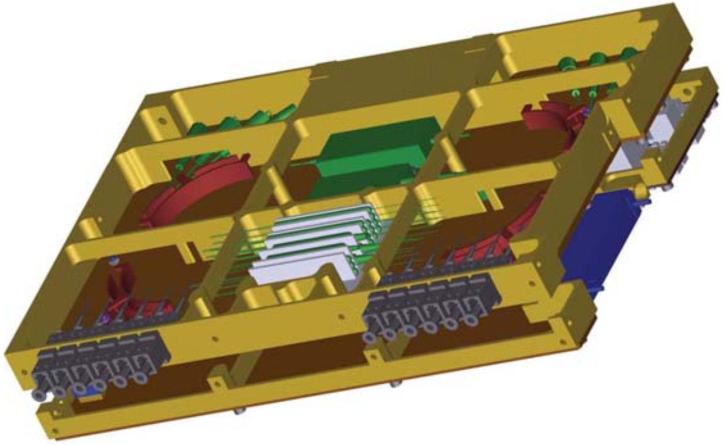


Fig. 2. Mechanical layout of the FBG module

The key elements of the IU are:

- Power supply. The IU is powered from the backplane interface. It uses a single 28V ±4V power supply.
- SSB: Space Serial Bus [2] data interface compatible with the internal RTU2015 bus
- Control FPGA: It is a ProASIC3 FPGA from Microsemi, including an ARM Cortex – M1 microprocessor. It processes the acquired signals from each channel, calculates the centroid of the FBG peaks and converts the frequency into the physical parameter to be measured (temperature, strain). It also manages the SSB communications. This block also features an EEPROM (not pictured) to store the calibration parameters.
- Photodiodes + acquisition electronics: convert the received optical signals into electrical signals, which are amplified and acquired. Variable gain amplifiers are used to accommodate up to 30dB of optical power range to account for differences between channels and sensors, effects of radiation and ageing or other defects that can cause an additional attenuation in the light path.

•Tunable Laser (TL): The TL is a fiber ring laser delivering an optical signal with a wavelength that is swept between 1500 and 1600nm every 100ms. A SOA is used as active medium and a tunable filter is used inside the ring to control laser emission wavelength.

•Internal optical distribution network: delivers the TL output to the external channels, to be distributed to the FBG sensors, and to the internal reference channels, that are used to identify the reflected wavelength. The distribution network also incorporates a set of optical switches (normally open) used to provide protection against failures in the fibers. In case a fiber break occurs, the switch can be closed to provide a path to illuminate the end section of the fiber and avoid losing the sensors that are placed after the breaking point.

•Optical reference channels: Aimed at identifying accurately the FBG reflected wavelength, a Fabry-Pérot etalon and an optical add-drop multiplexer (OADM) are used.

B. Technical features

The presented architecture of the IU features 6 optical channels, with up to 20 temperature sensors on each one for a total of 120 sensors. However, the architecture can be expanded easily to accommodate more channels if required, depending only on the system requirements (number of sensors and physical / electrical constraints), since each channel is acquired independently and in parallel (simultaneously) with the other channels. 8 channels is seen as a practical limit for the chosen version of the FPGA and the specifications imposed by the RTU2015. Each fiber channel is provided with protection to a single-point fiber failure.

The full set of sensors is swept in 100ms (10Hz). The acquired parameters are stored, each one with its associated timestamp indicating the moment of the acquisition with an accuracy of 1µsec and can be transmitted to the system in the same time. Target wavelength accuracy of the system is ±2pm.

Calibration data for the sensors is stored internally in the unit, allowing the possibility to have either a common calibration curve for each type of sensor or independent calibration curve for each individual sensor for improved accuracy. Also, the unit is capable of addressing any FBG based sensor, and thus other type of parameters (such as strain, acceleration or pressure) are also addressable with this equipment.

The operating temperature for the IU is the same as for the RTU2015: -35°C to +60°C. Typical power consumption is around 12.3W. However, this value may be as low as 10.8W depending on the actual temperature of the unit, since an important amount of power (1.5W) is dedicated to the thermal control of the SOA device, which must operate at an internal temperature of 20°C in order to avoid performance degradation over time. The IU uses two slots in the RTU2015, and thus the dimensions are 160 x 233.5 x 52 mm3 (double eurocard format). Total mass of the IU is 1200 g.

These features are summarized in Table 1.

Parameter	Value
Number of channels (fibers)	6 (extendable up to 8)
FBG sensors / channel	20 x temperature sensors
Sampling frequency	120 sensors in 100 ms [10 Hz]
Wavelength Accuracy	± 2pm
Interrogator operating temp	-35ºC → +60ºC
Power Consumption	12.3 W (typical, with active thermal ctrl)
Mass	1,200 g
Module's Dimensions	160 x 233.5 x 52 mm^3 *Double Eurocard format*
Tolerant to one failure on each fiber thanks to optical switches	

Table 1. Interrogation unit key features

III. FBG TEMPERATURE SENSOR

The FBG temperature sensors are fully dielectric and have a very small form factor (20 x 6.35 x 2mm) and low weight (1gr), while ensuring proper strain decoupling and robust handling.

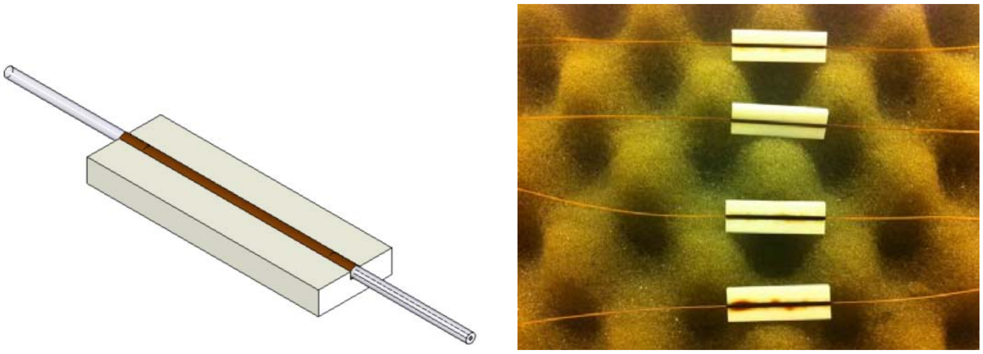


Fig. 3. Sensor virtual image and picture of 4 samples

Sensors have been designed to operate in the -196 to 125ºC range. Figure 4 shows the sensor response down to liquid nitrogen temperature and the sensor sensitivity (computed as the derivative of the second order fitting of the sensor response). Although FBG sensors are well known to have decreased sensitivities on low temperatures [3], the current design provides a 2,2pm/ºC sensitivity at -200ºC, which considering wavelength accuracy of 2pm yields accuracy better than ±1ºC.

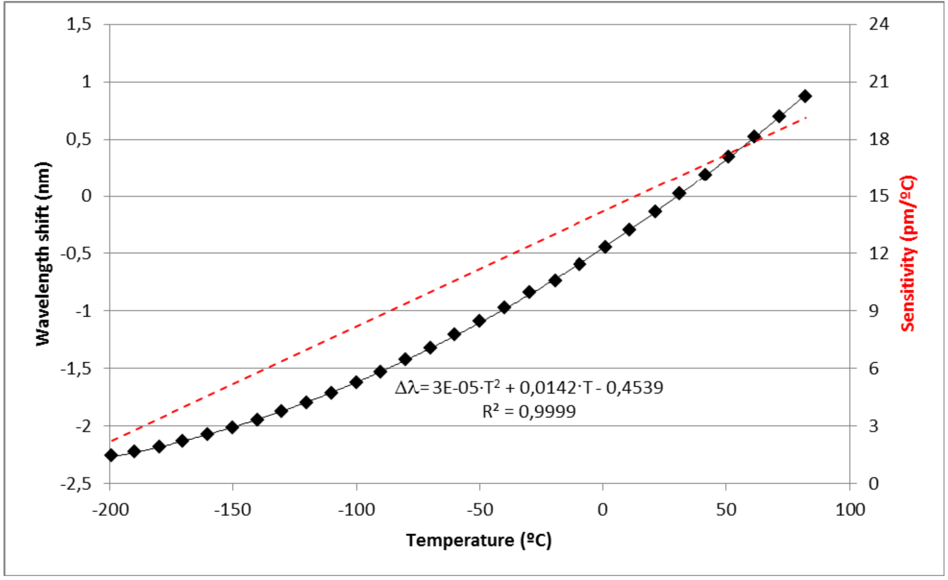


Fig. 4. Sensor response down to liquid nitrogen (reference temperature 30ºC)

Although sensors are provided with individual calibration formulas, these sensors can be employed over the -55 to 125ºC range using a common lookup table for all sensors on each wavelength band, while maintaining an accuracy of ±1ºC. If individual calibration formulas are used, accuracy over the -55 to 125ºC range is improved to 0.2ºC.

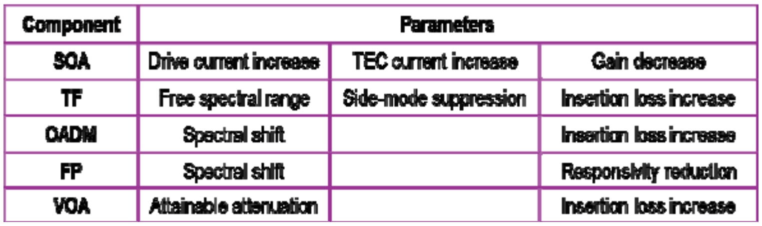
Regarding strain cross-sensitivity, the sensors were attached to an aluminum plate using both aluminium and kapton tape and using 3M Scotch-Weld 2216 adhesive. In all cases, the recorded response was identical to that of the loose sensors, thus proving proper strain decoupling.

Mechanical tests have been performed on the sensor, showing fiber pulling tension in excess of 6.5N and output bending radius lower than 10mm. Response time constant has been measured to be 4 seconds.

IV. QUALIFICATION OF PHOTONIC PARTS

In order to reach TRL5 on the technologies used in this development, some critical optical components have undergone a pre-qualification test campaign.

Couplers, isolators, photodiodes and connectors are optical parts used normally in space developments, so they have not been targeted for this test campaign. For the rest of optical components, critical parameters have been identified for this application, and they have been monitored during mechanical, thermal and radiation tests. The components tested in the campaign and the associated parameters are shown in the next table:



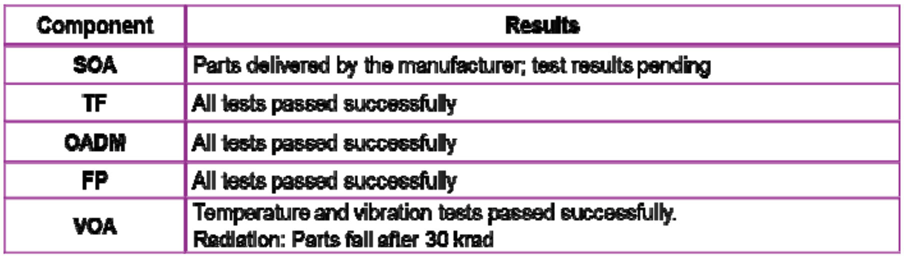
Component	Parameters		
SOA	Drive current increase	TEC current increase	Gain decrease
TF	Free spectral range	Side-mode suppression	Insertion loss increase
OADM	Spectral shift		Insertion loss increase
FP	Spectral shift		Responsivity reduction
VOA	Attainable attenuation		Insertion loss increase

Table 2. Testing parameters

The test conditions are:

- Temperature: -30°C to +70°C
- Vibration: sine, random vibration, SRS shock tests according to ECSS 10-03 standard.
- Gamma radiation: according to ESCC 22900 with a dose rate of 430 rad (Si)/h with intermediate steps for parameter measurements at 10, 20, 30, 60 and 100Krad

The next table summarizes the test results:



Component	Results
SOA	Parts delivered by the manufacturer; test results pending
TF	All tests passed successfully
OADM	All tests passed successfully
FP	All tests passed successfully
VOA	Temperature and vibration tests passed successfully. Radiation: Parts fail after 30 krad

Table 3. Summary of testing results

The SOA tests are being run at the time of edition of this paper. The tested VOA is a COTS version. It is suitable for launcher applications, whereas for satellite applications a Radiation Hardened version exists.

V. FOLLOWING STEPS

The present implementation aims to reach TRL5 for all components and technologies involved with the inclusion of the FOS demonstrator in the AvionicX prototype and the tests on the RTU2015 unit.

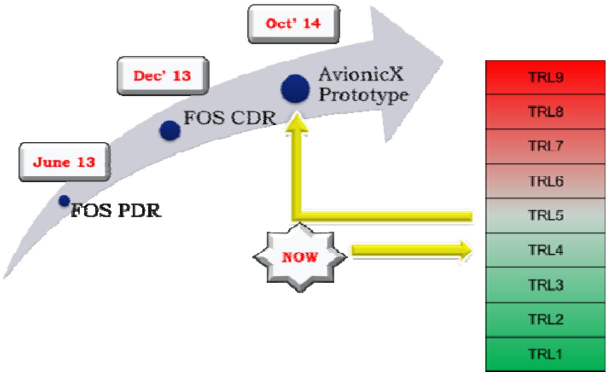


Fig. 5. TRL status of FOS solution

Present: a laboratory prototype has been built and used to validate the architecture, achieving target accuracy. Testing of critical optical components is being finalized.
September 2014: First complete IU prototype + FBG sensor arrays manufactured and ready for testing
October 2014: IU + FBG sensors tested (TRB)
Q1 2015: Validation of FOS IU within the RTU2015.

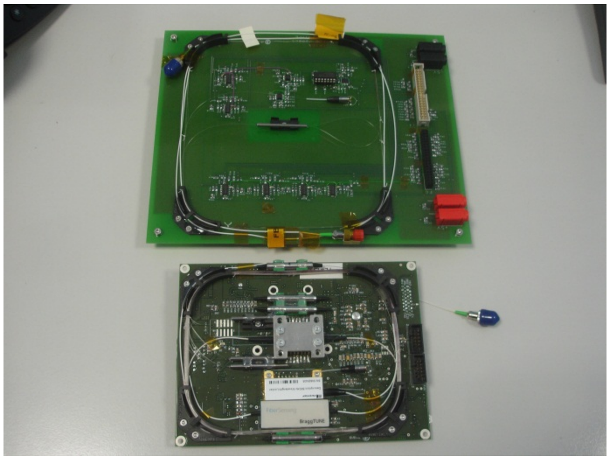


Fig. 6. Boards used for prototyping of the FOS architecture for space applications

VII. CONCLUSIONS

A complete FBG temperature monitoring subsystem for application in telecom satellites and launchers is being developed to be integrated as part of a Modular RTU with the capability to provide hybrid electrical-optical measurements. The system is currently in the prototyping phase (Engineering Model) and will undergo testing in Q4 2014 and Q1 2015.

The developed FOS module can interrogate up to 120 temperature sensors distributed in 6 optical fibers, providing redundancy to single point fiber failure on each channel. Target accuracy is ±2pm with a 10S/s sampling rate.

The developed sensor exhibits a very low weight and small form factor (comparable with standard thermistors), while providing a mechanically robust design (low bending radius at the sensor outputs and high fiber pulling strength) and ensuring strain decoupling. Good sensor operation on the -200 to125ºC range has already been demonstrated.

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